Consensus technical summary of the members of the review panel for Proof-of-Principle Proposals in Fusion Energy Science, June 8-11, 1998

Stellarator Proof of Principle (PoP) Program Proposal

1. Summary

The panel members conclude that the stellarator community is ready for a PoP program with a lead experiment based on the "quasi-axisymmetric (QA) stellarator," which is a concept based on a new direction, rather than a refinement of more standard directions. The members are concerned that the cost of the proposal is high in the context of the Fusion Energy Program and that the construction time for the lead experiment is long enough to slow down progress on the concept.

This lead experiment will focus on: (1) the role and usefulness of bootstrap currents in this version of the compact stellarator (A = 3-4); (2) beta limits; (3) the avoidance of disruptions; (4) demonstration of the control of neoclassical transport by proper configuration design; (5) control of turbulent transport, e.g. using enhanced confinement techniques ("transport barriers") developed in the tokamak program; and (6) the role of bootstrap current and magnetic shear in suppressing or enhancing magnetic islands and tearing modes. The closeness to standard tokamak operation of the main concept gives the expectation of achieving a high quality plasma in a new configuration a high probability of being achieved.

In endorsing the technical merit of the proposed lead experiment, the National Compact Stellarator Experiment (NCSX), the panel members recognized: (a) the significant innovative components of the proposal, (b) the strong theoretical basis for the design, (c) the experimental relationship to the tokamak which has a large data and theoretical basis, and (d) the strengths of the stellarator team in physics and engineering.

The proposed program also includes Concept Exploration (CE) experiments, theory, systems studies, and international collaborations. CE experiments include the Helically Symmetric Experiment at the University of Wisconsin, an upgrade of the Compact Auburn Torsatron, and possibly a new quasi-omnigeneous (QO) stellarator experiment. The panel members endorse the OFES plan that all new stellarator CE experiments and those with significant upgrades be reviewed as part of the broader CE process.

The US community has interacted closely with the international stellarator research community in developing new concepts for the present proposal. It is expected that the new directions will be viewed as complements to the presently established directions of the world program. A close international collaboration will enhance progress in the field.

2. Background Discussion on the Basis of the Proposal

The stellarator proposal is an outgrowth of commonly perceived weaknesses in the tokamak program which has been the mainline magnetic fusion program for about three decades. The tokamak has had an advantage over other magnetic fusion concepts in that it can produce plasma traps in a relatively simple magnetic configuration with confinement properties that has brought some experiments to regimes that are close to that needed to produce net fusion power. However, several limitations have been of concern in tokamak operation that may affect its viability as a power source. These include:

(1) The possibility of discharge termination by unplanned and perhaps wall damaging disruptions;

(2) The difficulty of achieving steady state current operation which can lead to premature fatigue due to stress from continual start-up;

(3) The likelihood of inducing current driven instabilities (from so-called neoclassical tearing modes) at high beta in the current profiles that are easiest to establish and sustain.

These crucial difficulties appear to be solved in typical stellarator designs. Sudden plasma disruption has not been observed in stellarator operation and the intrinsic property that rotational transform is produced by current in external coils allows for natural steady state operation. Further it is relatively straightforward to design for radially increasing rotational transform profiles that are not susceptible to neoclassical tearing mode instability. These three features of a stellarator provide for viable fixes to significant difficulties in tokamak operation.

The "price" for these fixes is the complexity that results from a stellarator magnetic field configuration. The shape of the magnetic fields is intrinsically 3-dimensional, and thus difficult to envision. More importantly, stellarator magnetic fields are not perfect traps. The magnetic field lines need not form surfaces, and a fraction of the collisionless particles orbits may not be contained due to intrinsic helical ripple (this latter situation is particularly relevant to charged fusion products that when lost would directly impinge on plasma facing surfaces, at perhaps selective "hot spots"). Hence a viable magnetic field design is quite crucial for favorable energy containment, both to contain thermal particles to low neoclassical losses as well as to contain energetic particles that arise from beam injection and fusion products.

Mainline stellarator research projects have existed in Japan and Germany for over two decades. They have demonstrated that energy containment in stellarators in properly designed magnetic fields produce thermal containment properties comparable to tokamak L-mode. Modest improvement of containment has been achieved in stellarator H-mode discharges, and recently W7-AS has achieved a confinement enhancement factor of 2.5 over standard operating conditions. As in tokamaks, the search for improved confinement regimes is of high priority in stellarators.

The main direction in stellarator research in Germany has been to develop a near-omnigeneous configuration where the collisionless motion of particles hardly deviates from a flux surface. Such a property suppresses bootstrap current, which is essential for these machines as they are designed with hardly any magnetic shear. They also seem to need large aspect ratio, which, together with beta stability limits, appears to lead to power producing systems with low surface power density.

An alternate tack that has been developed in recent years has been the study of a quasi-symmetric configuration. Two types of symmetry can be exploited, quasi-helical symmetry and quasi-axisymmetric symmetry. Both symmetries limit the deviation of charged particles from closed flux surfaces. An experimental program that will study helically symmetric systems is now in place at the University of Wisconsin. The main thrust of the present proposal is to investigate quasi-axisymmetric (QA) configurations at the Princeton Plasma Physics Laboratory.

There are several striking features in the QA configuration:

(1) A compactness that allows for an aspect ratio of ~ 3 which is typical of a tokamak, and which can lead to higher wall loading capability than high aspect-ratio stellarators.

(2) Tokamak-like magnetic fields, which allow the rotational transform producing coils to be saddle coils, rather than coils that thread around the machine. This features allows for more flexibility in determining parameters for optimal operation.

(3) Compatibility of internal bootstrap (or ohmic) currents with external currents for generating desirable rotational transform profiles. The two current sources augment each other. The induced bootstrap current that produces rotational transform "heals" rather than destabilizes magnetic islands in rotational transform profiles that increase with radius.

(4) Stability studies indicate that beta values in up to 5% can be MHD stable in a compact QA configuration. This value is even higher than is planned in many tokamak reactor scenarios; nonetheless a rather large reactor size is still envisioned and even higher beta limits may be needed to obtain the flexibility to have smaller power plants.

These features by and large make the QA stellarator quite promising as a mainline experiment. The proposal exploits in a natural way the expertise of the Princeton group in tokamak operation. Operation of the QA should be very similar to tokamak operation. Indeed the concept can be viewed as an extension of the tokamak concept to a region where stellarator and tokamak fields interact in a mutually beneficial way to solve some of the traditional shortcomings that otherwise exists in both these concepts. There is a high degree of confidence among committee members that interesting plasma parameters would be achieved by the Princeton group on the QA experiment. Nonetheless, there was a realization that the design step from tokamak to stellarator is rather ambitious and unforeseen problems may arise.

The second concept that is being proposed for stellarators is a compact quasi-omnigeneous device. The thrust of the concept is to achieve quasi-omnigeniety and compactness in a configuration that can attain stability at relatively high beta. This concept has made rapid progress during the past year and it is seen as a prime candidate for PoP level of support after the conclusion of the present QA experiment and if the results of the CE investigation are favorable. The quasi-omnigeniety allows for weak neoclassical effects so that the bootstrap current is not high (hence the rotational transform profiles remain under external control even at high beta) and the neoclassical diffusion is quite modest. Calculations of fusion particle losses indicate that about 10% of the alpha particles have prompt loss, indicative that most of the alpha particles will be trapped in the quasi-omnigeneous fields. This configuration can have substantial shear, and hence is not subjected to large island formation, as low-shear stellarators are when resonance arises. In this concept, many different parameters are optimized simultaneously.

3. Basis for Support Level

The panel explored the issue of whether the important physics for the QA concept should first be explored at the CE level before undertaking a PoP experiment. Several issues led to the conclusion that the PoP level is proper for this experiment. These included the aforementioned contact with the tokamak data base, which provides both data and theory to guide the QA stellarator. Also, the international stellarator program has provided codes and data which help establish the design point of the proposed experiment. On the experimental physics side, the panel noted that the beta limit is likely to be "soft," and thus its study requires both the proposed heating power and the ability to do a good job on the power and particle balance. Other physics issues, e.g. evaluation of the role of magnetic islands, will require extensive diagnostics and operational pulse length.

The committee also examined the question of whether the PDX facility is the proper facility if a QA experiment is approved. Concern was expressed that this facility, and in particular the vacuum vessel, might be so constraining as to limit the physics issues addressed, e.g. involving the aspect ratio or in the ability to use simple modular coils which could provide a more robust configuration. In the end, the panel concluded that although the vessel is not ideal, the cost saving are probably significant enough to offset any limiting constraints. The poloidal field coils, together with the proposed saddle coils to generate magnetic shear, should provide a significant degree of flexibility for the experiment. The power and other facilities available are a significant asset which should be utilized by the US program.

Although the facility should be capable of conversion to a QO geometry several years downstream (as discussed in the proposal) the decision and specifics of such a conversion should undergo review by the fusion community before it is undertaken. This decision should be made in the light of the knowledge gained from all QA and QO experiments.

4. Technical Issues

The panel members had several technical concerns which need to be addressed as the stellarator program proceeds. These included possible limits due to MHD activity during plasma startup, when the magnetic configuration may have a hill, and whether power and particle handling will be adequate as the experiment moves to higher power and longer pulse lengths. It is recommended that the stellarator community review such issues as it proceeds with a detailed experimental proposal.

The possibility of Alfvén instabilities effecting beam containment when heating is attempted was brought up, as it has been found to be deleterious in some stellarator experiments. Though such phenomena does not appear to be the rule, better theoretical understanding of this phenomena should be developed.

Numerical studies of stellarators are mathematically extremely subtle especially when islands develop at finite beta. Continued verification of known experimental results with theoretical code predictions should continue to ensure that the conceptual understanding is accurate.

5. Cost and Schedule Issues

The proposed stellarator program is rather large with total annual funding ramping to $30M by FY2003 (i.e. by the fifth year of the POP program). This amount is equivalent to the largest POP funding recommended by the FESAC POP guidelines. The scale of the stellarator POP is determined by the NCSX experiment. The four year construction cost of NCSX is $35M. After construction, the annual cost for operation and upgrades is $20M/year. Slightly less than $10M/year is requested for the costs of supporting theory, stellarator CE experiments, and international collaborations. Since the total cost of the stellarator POP is substantial, the panel members urge that the stellarator community seek ways to reduce costs.

Another concern of the stellarator program is the relatively long time needed to establish experiments in the NCSX facility. Since the scientific results from NCSX are important for the evaluation of this confinement concept, the time required to begin experimental operation should be shortened if possible.

6. Reactor Issues

There are still concerns about the viability of a stellarator reactor that might result from the present concepts. If the physics issues in the stellarator are solved, a stellarator reactor will have several advantages over the tokamak: lack of disruptions, steady-state operation, and the lack of auxiliary current drive. The cost savings of the latter, both in capital and operation, may balance added costs from the complexity of the magnetic coils. However, the beta of the concept as presently proposed is about 5%, and thus on the low side. It is the panel's understanding that the presently estimated cost of electricity is comparable to that of the advanced tokamak, and thus higher than the US market will accept today. Further innovation and simplification of the stellarator concept may still be needed for it to be a commercially successful fusion energy reactor.